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Coalescence of Levitated He II Drops

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We describe experiments to study the coalescence of He II drops levitated in a magnetic trap. Using a high speed CCD camera, we have produced movies of drops coalescing at temperatures as low as 0.7 K. We examine some interesting features of the motion during and following coalescence.

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1. INTRODUCTION

When two drops come into contact, surface tension will act to form a larger drop with smaller surface area. The coalescence process starts from a singular condition where the drops come into contact at a point, and the curvature of the surface in the vicinity of this point is arbitrarily large. Because of this highly singular initial condition, the theory of coalescence presents unique challenges and has received considerable attention. It remains an open problem in fluid mechanics. Understanding coalescence is important to many other fields. Problems as diverse as raindrop formation[1], the underwater noise of rain[2], and the description of two phase dispersions and sintering[3] have motivated research in this subject.

In order to study the motion of the free surface of coalescing drops, experiments have to be carried out in conditions such that the drops are not in contact with any surface. For this reason, many experiments have looked at the behavior of drops colliding with each other in flight[4]. There have also been experiments carried out with drops acoustically levitated in a second inmiscible fluid. However, the presence of a second fluid complicates the coalescence process because this fluid must be drained away from the region between the drops before the surfaces make contact. This can lead to a significant change in the coalescence process. For example, the presence of a second fluid between the drops can cause the drops to bounce from each other[4]. Coalescence can also be affected by surfactants, and so to perform controlled experiments it is necessary to use very clean liquid.

Theoretical studies of coalescence have tended to focus on two distinct aspects of the problem. The first concerns the general features of the surface morphology as a function of the time after contact. Depending on the impact velocity, relative size of the two drops, viscosity of the fluids, etc, the material in the two initial drops may form a single drop, or may break up into multiple drops[5]. The second area of interest concerns the early stages of coalescence, during which the small region of contact between the drops grows rapidly. It was proposed by Frenkel[6] that the radius of the neck should vary as the square root of the time. Recently, it has been argued that the radius should not follow a simple power law. Instead, even at zero impact velocity, the surface of the two coalescing drops will evolve in time in a way such that multiple connections take place, thus causing the entrainment of toroidal bubbles around the neck of the coalescing drops[7].

Because of the issues just mentioned, experiments with helium drops in a microgravity environment are of considerable interest. In microgravity, there is no need for a second fluid surrounding the drops. Drops can be brought together with any desired impact velocity v_{impact}, and it should be possible to study the coalescence process in the limit as $v_{\text{impact}} \to 0$. Helium can be prepared with extreme purity and without any surface contamination. Finally, there is the possibility of studies of helium in the superfluid state, where the viscosity of the superfluid component becomes zero.

Our current experimental setup allows us to levitate drops of helium of up to 2 cm in diameter using a static magnetic field. In the region within 1 cm from the center of the magnetic trap, the effective acceleration due to gravity g^* is approximately $0.01g$. As a result, we are able to study the free surface of coalescing drops that have an impact velocity as a small as a few cm per second. As will be described below, we are also able to study coalescence for much smaller v_{impact} by using tethered drops. The density of the vapor surrounding the drops can be made as low as is desired by reducing the temperature. In this paper, we discuss the results obtained from coalescence experiments in our magnetic trap. The events were recorded using a high speed video system. We discuss some qualitative features of the motion and compare them to theoretical predictions.

2. EXPERIMENTAL DETAILS

In our current setup, we levitate helium drops using a strong static magnetic field produced by a superconducting solenoid. The details of the magnetic levitation, and the variation of the potential energy in the vicinity of the trap have been presented in an earlier paper[8]. We have developed a number of methods that can be used to insert drops into the trap.

The procedure for studying the coalescence of drops is as follows. One drop is first introduced into the magnetic trap. Usually, this is done with the temperature of the cell below the lambda point. After the drop has come to rest in the trap, we begin to add helium slowly through a capillary to produce a second drop. This capillary ends at a point approximately 1 cm from the center of the trap. When the drop that forms at the end of the capillary has reached the desired size, we perturb the drop by introducing some more helium quickly into the capillary. This gives the drop enough energy to break free from the end of the capillary. It then falls into the trap and coalesces with the first drop. The impact velocity is then determined by the difference $\Delta\phi$ between the magnetic-gravitational potential ϕ_1 at the end of the capillary and the potential ϕ_2 at the surface of the drop in the trap. This difference depends to some extent on the size of the drops, but is normally such that the impact velocity is of the order of a few cm sec^{-1}.

As an alternative, we can allow the drop on the end of the capillary to grow slowly until it comes into contact with the levitated drop. In this way we can achieve essentially zero impact velocity. However, with this method we are not really studying the coalescence of two free drops since one is still in contact with the capillary.

The coalescence events were recorded using a CCD camera capable of taking 964 frames per second at a resolution of 254 x 254 pixels. We view the drops from above through a standard telephoto lens. The drops were illuminated with intense white light from below. By focusing the camera on a reference scale, we were able to determine the distance that corresponds to one CCD pixel, and to use this to measure the size of the drops.

3. RESULTS

Using the setup just described, we have produced a number of high speed movies of coalescence. The observations have been made at different temperatures in the range 0.7 to 1.4 K. The radius of the drops varied between 0.1 and 1.3 cm. In Fig.1, we show the coalescence at 1.39 K of drops of radius 0.18 and 0.67 cm. The 0.67 drop is levitated in the trap, and the 0.18 drop is attached to the end of the capillary, so the impact velocity is essentially zero. The capillary wave traveling around the surface of the larger drop can be seen in this figure.

In Fig. 1, it is not possible to resolve the growth of the neck between the

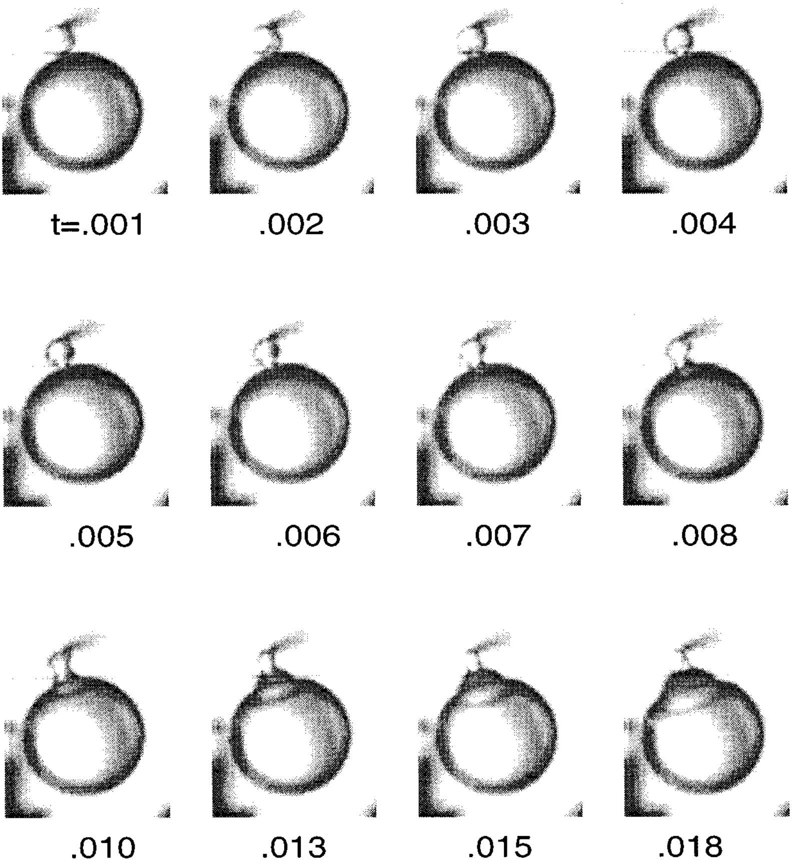
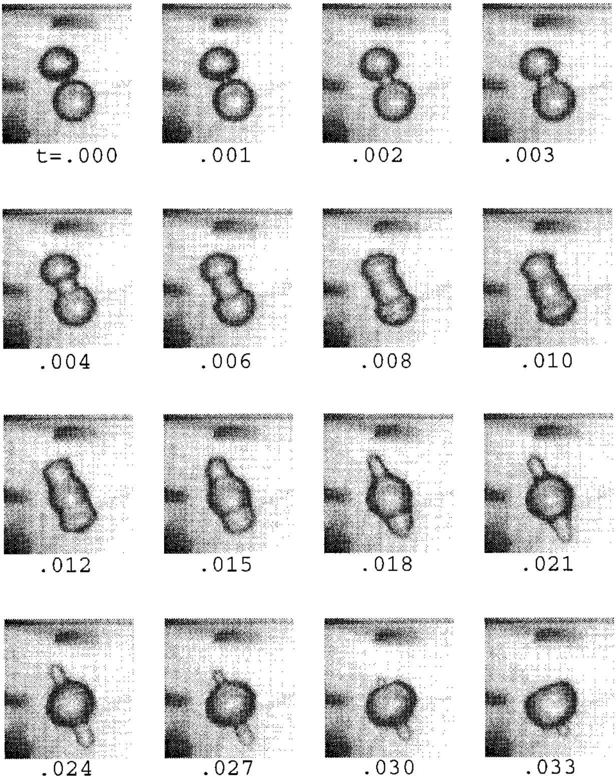


Fig. 1. The coalescence of two drops at 1.39 K. The frames are labeled by the time in seconds.



t=.000 .001 .002 .003
.004 .006 .008 .010
.012 .015 .018 .021
.024 .027 .030 .033

Fig. 2. The coalescence of two drops of approximately the same radius at 0.73K. The frames are labeled by the time in seconds.

drops because one of the drops is very small. The early stage of coalescence can be made out more clearly in coalescence between drops of approximately equal size. Fig. 2 shows the coalescence of drops with radius 0.21 and 0.25 cm. It can be seen that the growth of the neck takes place within the first few msecs during which time our camera can only record a few frames. To study the initial stages of neck growth will require either the use of a higher speed camera or the study of larger drops which will change shape more slowly. Experiments with larger drops can only be performed in space. So far, we have seen no evidence for the formation of bubbles in the vicinity of the neck, but this may well be because of the limited resolution of the recording system.

We have found that even when the impact velocity is very small, the liquid does not always remain as a single drop. This is presumed to be because of the low viscosity of helium. We are currently studying the influence of temperature and drop radius on this effect.

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